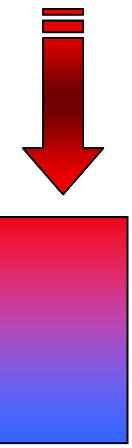
Idaho National Laboratory

Thermal Wave Imaging

1-D thermal wave imaging

Periodic thermal excitation gives rise to a periodic temperature field throughout the sample. The classical thermal wave method for thermal diffusivity measurements is based on a simple dispersion relation for harmonic heat diffusion in one dimension in a homogenous isotropic solid. In these expressions, κ is the thermal diffusivity, ω and q are the angular frequency and wave number.

$$Q = Q_0 \sin(\omega\, t)$$
$$(laser \quad heating)$$

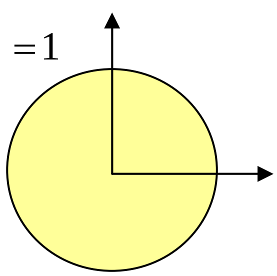


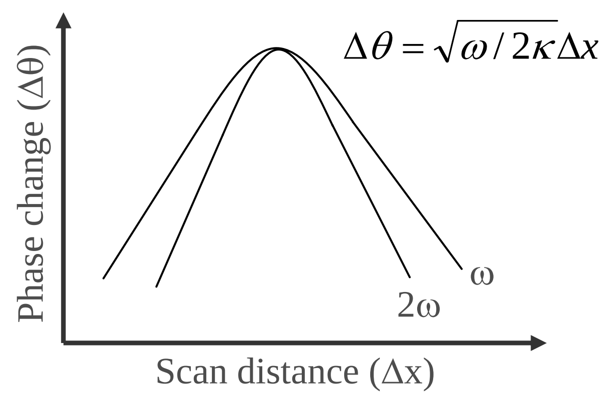
$$T \sim e^{(iqx - i\omega t)}$$
$$q^2 = i\omega / \kappa$$
$$\Delta\theta = \mathrm{Re}(qx) = \sqrt{\omega / 2\kappa}\,\Delta x$$

3-D thermal wave imaging

Homogeneous isotropic material ($\kappa_1 = \kappa_2 = \kappa_3 = \kappa$)

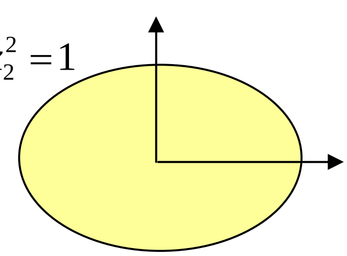
$$\kappa_1 x_1^2 + \kappa_2 x_2^2 = 1$$

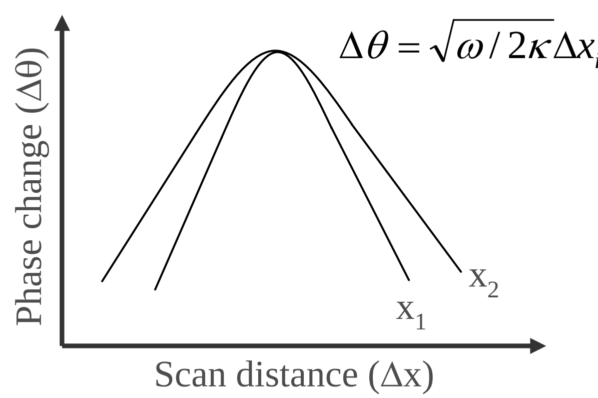




Homogeneous anisotropic material ($\kappa_1 \neq \kappa_2 = \kappa_3$)

$$\kappa_1 x_1^2 + \kappa_2 x_2^2 = 1$$





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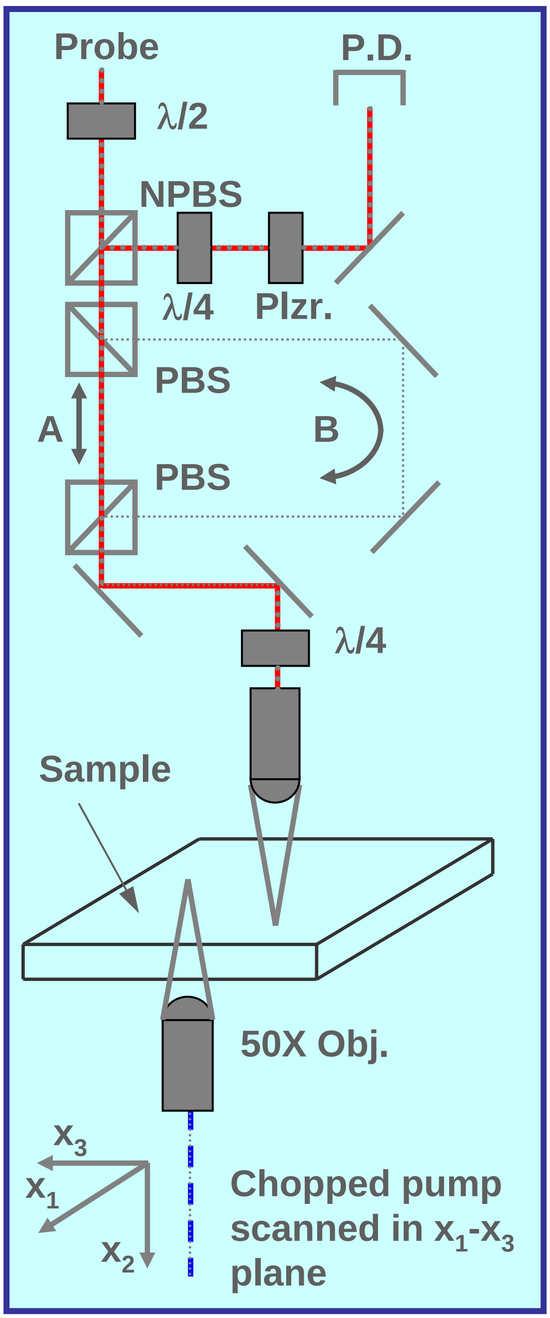
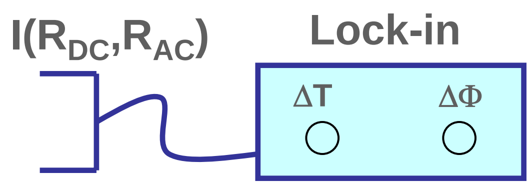
Thermal Wave Imaging: Experiment

Experimental setup



Sensing small ΔT



- Small temperature induced changes in optical reflectivity are measured with the aid of a lockin amplifier
- Typically, the phase output of the lockin is analyzed because this quantity is insensitive to variations in background reflectivity

Sample specification

- 200 nm polycrystalline chromium film (thermally isotropic)
- Single crystal quartz substrate (trigonal symmetry)
- C-axis coincides with x_1 axis and hexagonal edge coincides with x_2 axis

$$\kappa = \begin{vmatrix} \kappa_{11} & & \\ & \kappa_{22} & \kappa_{23} \\ & \kappa_{32} & \kappa_{33} \end{vmatrix}$$

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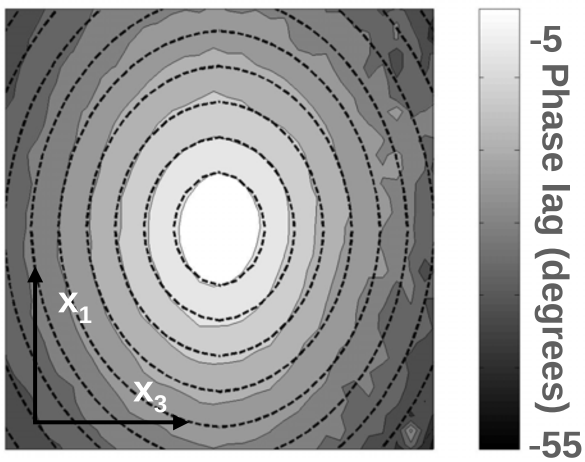
Thermal Wave Imaging Application: Thermal Anisotropy

Phase contour



Phase contour reveals thermally anisotropic nature of substrate for kilohertz range modulation

Observations

Lateral resolution is related to the optical spot size (~1μm).

Depth resolution is related to thermal constants and modulation frequency (1 MHz→100nm for chromium film/single crystal quartz substrate).

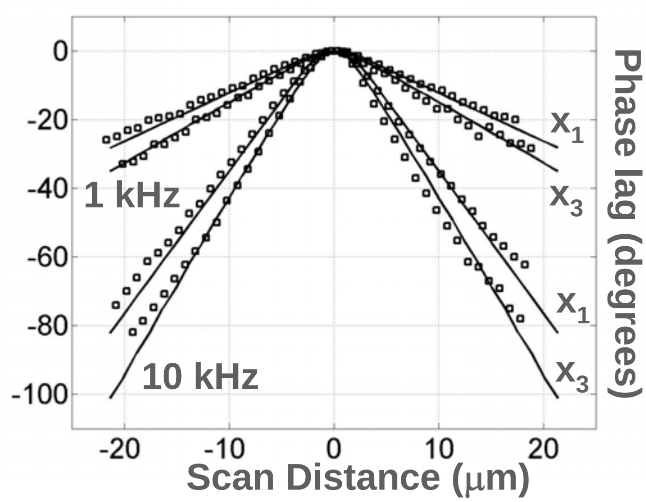
A good fit to the data was obtained by setting contact resistance to zero.

Observations

The phase contour exhibits symmetry about the x1and x2 axes. For second rank tensor properties the symmetry exhibited by trigonal systems cannot be distinguished from hexagonal systems.

The anisotropic nature of this problem imposes a restraint on choosing the contact resistance. Namely the theory should correctly predict the difference in slope of the phase lag along the x1 and x2 directions.

Phase profile



The profile shows conjugate relationship between changes in position and changes in frequency

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